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The Cause of Spatial Disorientation

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SUMMARY

We here present a model including visual-vestibular interactions describing the basic properties of the human spatial orientation system. It hence also explains and describes spatial *dis*orientation. The model indicates that spatial orientation should at least be characterised by four variables: linear acceleration and velocity, angular velocity, and attitude. Perception of the latter is part of the subjective vertical. Due to visual-vestibular interactions at different levels, these variables are partly independent, and may therefore behave differently. This is demonstrated by two examples concerning a takeoff. A moderate takeoff is simulated by means of a Stewart platform, a high G-load takeoff, like the catapult launch on an aircraft carrier, by a centrifuge. Model predictions are shown and concisely discussed, with further reference to previous papers on this matter. This elaboration, and the notice that we normally (in case of self propelled motion) need a sense of self motion for self control of body motion, leads us to the following conclusion: the main cause of spatial *dis*orientation is the indistinguishability of accelerations due to motion (i.e. inertial accelerations) and those due to gravity. This problem is further enhanced by a limited range of (near) perfection of our visual and vestibular sensors. Unfortunately, the high performance military flight environment is definitely out of that range.

INTRODUCTION

If we had evolved in space, we would not have encountered problems with spatial disorientation (SD) as we have on earth. In space, i.e. in weightlessness, the only accelerations met are those due to motion (inertia), and our vestibular system is capable of estimating these motions adequately. On earth, however, we are also faced with gravity (masses attract each other), and by Newton's second law this gives rise to the gravitational acceleration. The problem we have on earth is that both accelerations are physically different but indistinguishable (Einstein's equivalence principle). As a consequence, there are no sensors that can make this difference, and this also holds for our vestibular apparatus (see below). To control our motion, however, we should know how well an intended motion has finally been achieved. The most simple way to describe this control is by means of a simple feed back loop as sketched in Fig. 1.
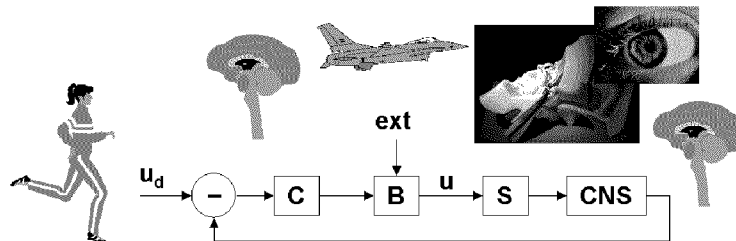

Fig. 1. Simplified representation of the human motion control loop. A desired body state (u_d), directs a controller (C) within the central nervous system (CNS) generating motor commands that drive the muscles in the body (B). The body can also be moved by external sources like that of an aircraft. The actual state of the body (**u**) is registered by (among other things) the vestibular apparatus and the visual system, which signals are processed by the CNS for comparison with the desired body state.

Hence, for the purpose of motion control, inertial accelerations should be separated from gravitational accelerations, the latter determining our sense of attitude, and our sense of motion should be exact. As will be illustrated by the following examples, these conditions are not always met.

If, for example, we are rotated on and about an earth vertical axis with a constant velocity, our sense of (angular) motion will vanish within tens of seconds (Fig. 2). If we are rotated about an earth horizontal axis (Fig. 3), this also happens, but, because we then also "feel" a change of gravity with respect to our body, we interpret this motion then as if we are moved like a gondola on a Ferris wheel (Mayne, 1974; Mittelstaedt et al., 1989). Another important phenomenon concerns the somatogravic illusion (Graybiel et al., 1947; see Fig. 4). This illusion refers to a perception of tilt when only submitted to a linear acceleration. It has also been shown that this illusory perception of tilt only comes forth gradually within a period of (tens of) seconds. Graybiel and Clark (1965) subjected several subjects to a centripetal acceleration in a centrifuge to show this (see Figs. 5 and 6).
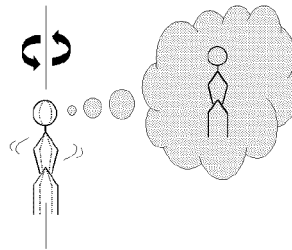

Fig. 2. After several tens of seconds of constant angular velocity about an earth vertical axis, motion perception has returned to a stand still.
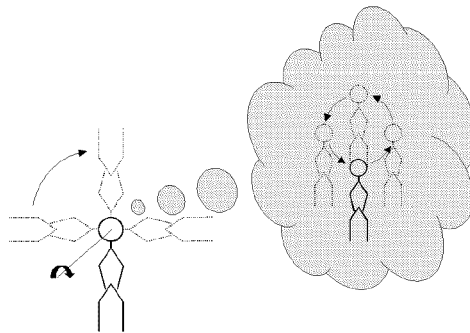

Fig. 3. A rotation about an earth horizontal axis results in a disappearance of angular motion sensation too, but here a Ferris wheel like motion results due to the relative motion of gravity about the subject.
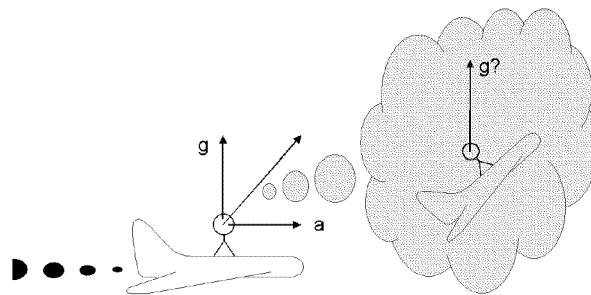
Fig. 4. Somatogravic effect. During linear horizontal acceleration (**a**), the direction of the resultant acceleration is interpreted as that of gravity (**g**), resulting in a sensation of tilt.
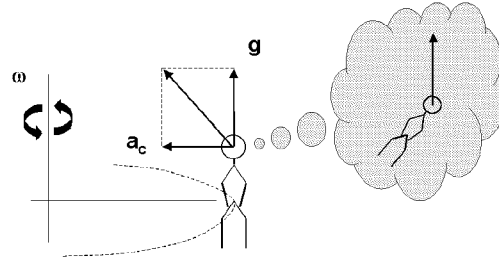
Fig. 5. Somatogravic effect. During centrifugation a centripetal linear acceleration $a_c = \omega^2 r$, with r the radius of the centrifuge, can be exerted to a subject for periods of time, much longer than induced by mere translation. Also in this case will subjects feel tilted, like in Fig. 4.
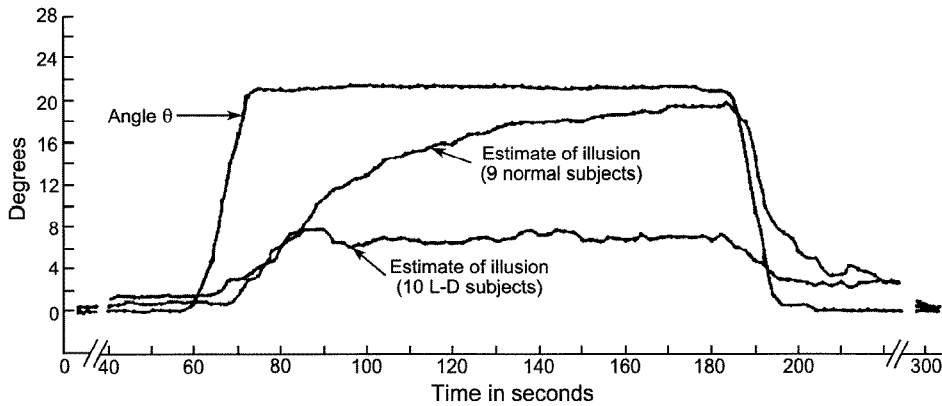
Fig. 6. Average estimated angle of tilt (θ) as observed by 9 normal subjects and 10 labyrinthine defective (L-D subjects), experiencing a centripetal acceleration of approximately 0.4g from. t=±60 to t=±185 s (after Graybiel & Clark, 1965).

Fortunately, there is some redundancy of information normally present, of which the visual cues are most important. We can also "see" what is up and what is down. Trees and houses should (normally) be upright, and the horizon horizontal. In addition there are somatosensory (pressure) cues, sometimes auditory cues, and cognition is at stake as well. This makes the description and explanation of spatial (dis)orientation a complicated matter, and we will, for the sake of simplicity, confine this paper to the two most important, that is to the vestibular and the visual subsystems.

First, some basics with respect to motion and attitude will be dealt with, followed by a theoretical framework that will serve the purpose of elaborating a model that may mathematically describe spatial orientation and motion perception. This model is built on knowledge of the vestibular apparatus and the subsequent processing of its afferents by our central nervous system (CNS). A most simple description will be used representing the processing of visual cues. Visual-vestibular interactions finally result in the (predicted) perceived motion and attitude. We have previously performed a series of flight simulator takeoff experiments using a Stewart platform, where experienced pilots judged the motions of different motion filter settings (Groen et al., 2001). As an example of the use of the currently presented model, we will simulate these simulator motions, in addition to those of a real takeoff, to explain the differences observed. A similar set of calculations will be presented concerning a catapult launch that can be simulated by use of a centrifuge. Because certain parts of the concept presented here have been published previously (Bos et al, 2001; Bos & Bles, 2002), we will only present the main flow of thoughts resulting in the final model, without focusing on details.

BASICS

Inertia and gravity

If we are moved in space, there are only six degrees of freedom (DoF) to be dealt with. We can be translated, giving rise to a change in position or velocity, and this may be characterised by the linear acceleration $\mathbf{a} = d^2\mathbf{x}/dt^2$, a vector with three components along three (orthogonal) axes. A rotation may additionally change the orientation, and this can be characterised by a three component angular velocity vector $\boldsymbol{\omega}$. Within each of our inner ears there are three more or less orthogonal semicircular canals (SCC), filled with fluid (endolymphe), which fluid will lag the head due to inertia. A piston-like valve (culupa) detects this flow of fluid, and signals the head rotation. Due to friction and the fact that the cupulae are fixed to the head, the fluid flow is damped, such that the neural canal signals are proportional to a high pass filtered angular velocity signal (e.g. van Egmond et al., 1949; Robinson, 1977). This implies that the SCC are insensitive to constant angular head velocity, and this is just what causes the illusions shown in Figs. 2 and 3.


Fig. 7. A set of three semi-circular canals detect angular motion within each inner ear. Within the sac closing the three loops, additional hair cell layers with crystals on top (the otoliths) detect linear acceleration (see Fig. 8).

Within the sac connecting the canals, there are two layers of heir cells with crystals on top (the otoliths, see Fig. 8, which crystals have a higher specific density than the surrounding matter, such that these will lag due to inertia too, here to linear motion ($\mathbf{a} = d^2\mathbf{x}/dt^2$). However, these otoliths will also be attracted by gravity on earth (see Fg. 9, and they will also signal proportional to gravity ($\mathbf{g} = \mathbf{F}_g/m$). Therefore, also these otolithic sensors are not capable of discerning inertial from gravitational accelerations. This results in 9 DoF that have to be dealt with on earth (i.e. 3 inertial acceleration components, 3 gravity components, and 3 angular velocity components). For the remainder we assume that the otoliths transduce the resultant acceleration, or specific force, near perfection (e.g. Merfeld et al., 1993), i.e. their output is proportional to $\mathbf{f} = \mathbf{a} + \mathbf{g}$.
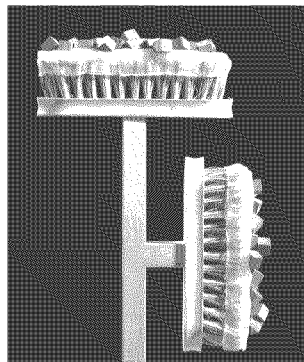

Fig. 8. A craftsman's impression of the otoliths.
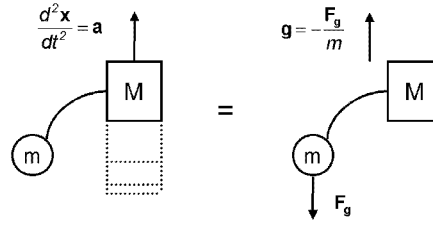
Fig. 9. Schematic representation of an otolithic crystal with mass m, connected by a hair functioning as a leaf spring to the body with mass M. If in space a force is exerted to the mass M, it will be moved with an acceleration a =d²x/dt² = F/M. Due to inertia, the otolith mass m "wants" to remain in place, but it is dragged via the spring by M upwards, finally resulting a steady state condition that is equal to a condition of rest on earth, where the mass m is attracted by gravity. As a consequence, the gravitational acceleration should be directed opposite to the gravitational force vector.

As stated in the introduction, the accelerations due to motion (inertia) en due to gravity are indistinguishable, and if we would not discern gravity as such, we might feel like an astronaut within five minutes ($\Delta x = \iint g dt^2 = \frac{1}{2} g t^2 \approx 440$ km, with $g = 9.81$ m/s² and $\Delta t = 300$ s). Obviously we do not feel this, and apparently our CNS does do something to the otolith afferents to make the distinction. Another example includes tilt. When tilted on earth, the gravitational acceleration may be exactly equal to the resultant of gravity and an acceleration forward and slightly downward (see Fig. 10) In the first example, some CNS-processing on otolith afferents only is requested, while in the second example, angular information from the SCC may aid in the solution to estimate motion and gravity. How this function of the CNS may be described mathematically is summarised in the next section on a spatial orientation model.
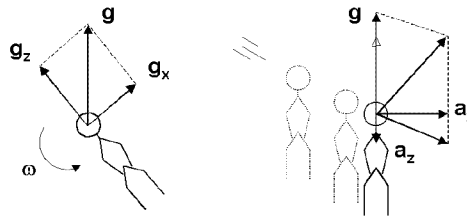
Fig. 10. The gravitational acceleration during tilt may be equal to the resultant of the gravitational and an acceleration forward and slightly downward.

A SPATIAL ORIENTATION MODEL

Vestibular function

To know inertial acceleration **a** (i.e. due to motion), the gravitational acceleration **g** should be subtracted from the gravito-inertial acceleration, or specific force **f**: $\mathbf{a} = \mathbf{f} - \mathbf{g}$. However, we "measure" **f** with respect to the head, while **g** is earth fixed, and we should therefore calculate

$$\mathbf{a}_e = \mathbf{R}_\omega(\mathbf{f}_h) - \mathbf{g}_e. \tag{1}$$

with the indexes e and h referring to earth and head, respectively, and ω indicating that the rotation matrix is determined by the angular velocity as sensed by the SCC, for example. This, however, is only solvable if $\boldsymbol{\omega}$ and **g** are known exactly. In the previous section, however, we already showed that $\boldsymbol{\omega}$ is *not* known exactly, especially not during constant angular velocity. Moreover, there is no way to know **g** exactly. For we do not consider it a realistic option that gravity, both with its direction and magnitude, is known a priori, i.e. determined genetically, it should be estimated during life. One solution for this estimation has been given by Mayne (1974), who suggested a low pass filter to operate on otolith afferents. Because gravity is constant in an earth fixed frame of reference, while accelerations due to self propelled motion are variable, this indeed makes sense (see Fig. 11). Moreover, the temporal behaviour of the somatogravic effect as shown in Fig. 6 can also be explained by such a filter.
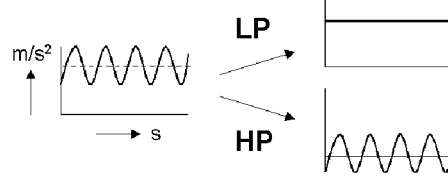
Fig. 11. Accelerations experienced during self propelled motion are composed of a variable component due to self motion and a constant offset due to gravity (Mayne, 1974). These components can be separated by means of a low pass (LP) and a high pass (HP) filter.

When also angular motions are reckoned next, the process of estimating both the gravitational component and the inertial acceleration, can be summarised as in Fig. 12.
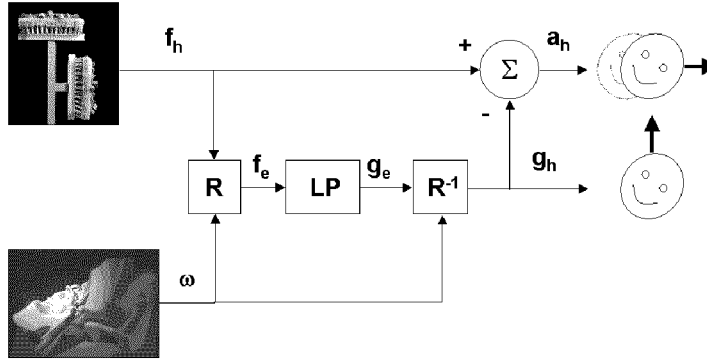
Fig. 12. Vestibular based spatial orientation model (after Bles & de Graaf, 1993). In the center of the model is a low pass filter (LP) operating in an earth fixed frame of reference. To obtain earth referenced components of the specific force (f_e) as sensed by the otoliths, canal information (ω) is used to rotate(R) the head referenced vector (f_h). Because the estimate of gravity (g_h) finally is given with respect to the head, an inverse rotation (R^{-1}) is needed to accomplish this. In this model, motion perception is realised by the inverse of the gravity perception, i.e. $a_h = f_h - g_h$.

Previously (Bos & Bles, 2002), we have shown that the mathematical equivalent of this model is given by

$$\frac{d\mathbf{g}}{dt} = \frac{\mathbf{f} - \mathbf{g}}{\tau} - \boldsymbol{\omega} \times \mathbf{g} \,. \tag{2}$$

where we have omitted the head referencing index. In fact, this description is the three dimensional equivalent of the two-dimensional model proposed by Mayne (1974).

Visual-vestibular interactions

Normally, we can also see how we move and how we are oriented in space, relative to other objects, or specifically relative to earth. This section will describe how these visual signals interact with the vestibular signals as described in the previous section. There are, however, many processes involved in visual perception, why this can not be described by one single interaction. First, retinal receptors should transduce the light quanta into appropriate action potentials, which involves photo-chemical processes. These neural signals next have to be transported to those parts of the brain that process them to result in perceptual responses. These processes are therefore relatively slow. Moreover, eye, head, and body movements are involved to acquire stable retinal images, and we also make inferences about our self motion based on visual information (vection, see below). And, last but not least, visual information has to be present in order to be useful anyhow. In the flight environment, especially that of military aviators, bad weather, darkness, or deceptive conditions may refrain the aviator from adequate visual information. Due to these limitations of the visual system, it is by no means trivial that vision is sufficient to determine a correct sense of spatial orientation.

Circular vection: If we are looking at a moving environment rotating about an earth vertical axis while sitting still, within several seconds we will experience a self rotation, instead of object rotation. This phenomenon is called circular vection. This sense of motion can be achieved by any visual stimulus, as long as changes in contrast are present. No interpretable structures are required, and a random dotted pattern suffices. This means that optic flow, characterised by velocity (here angular velocity) is the determinant of vection. If this sense of self motion is next combined with the deficient sense of self rotation during true self motion when rotating about an earth vertical axis in the dark at constant velocity, these two signals will just add to a veridical sense of self motion. This is illustrated in Fig. 13
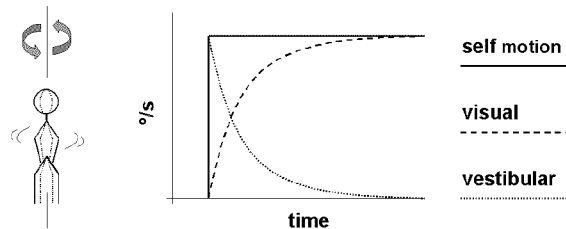
Fig. 13. Circular vection. When rotated about an earth vertical axis, visual motion will result in a slowly increasing sense of self motion, while true body motion will result in a slowly decreasing sense of self motion. The addition of both results in a true sense of self motion.

Linear vection: Something similar holds for linear vection, and this is most often exemplified by the train that is leaving the platform next to ours, inducing a strong sense of self motion in the opposite direction. Because this process is not counteracted by filtering of motion sensor signals as is the case with angular motion, linear vection is much faster than circular vection. Because we do not "see" acceleration, linear vection should be characterised in terms of velocity, and linear motion as sensed by the vestibular system (i.e. linear acceleration) should accordingly be integrated over time before it can interact with the visual velocity perception. At first order approximation we assume a linear weighted addition (c.f. Howard, 1997) of vestibular and visual velocity signals to take place to determine the final linear velocity perception. Vision will generally be dominant in this process (e.g. the train illusion).

Attitude perception: Things get more complicated when describing the visual-vestibular interactions with respect to attitude perception. Then, there are (at least) three factors of interest. First vestibular cues are at steak, as described in the previous section. Second, visual cues can be separated in polarity and frame information. Trees and houses generally point upward, while horizontal and vertical structures aid in determining horizontality and verticality. Lastly, there is also a sense of verticality determined by our own longitudinal body axis. This effect is most evident in weightlessness, when subjects can still indicate their sense of verticality, which, generally aligns with their longitudinal body axis. This contribution is called the idiotropic vector (Mittelstaedt, 1983). These contributions are sketched in Fig. 14, and they are also assumed to interact by means of a linear weighted addition.
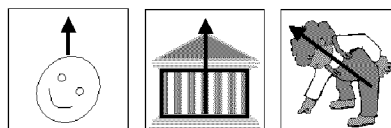

Fig. 14. Three components attributing to attitude perception: vestibular, visual and idiotropic cues. Vestibular perception can be described by a model like that of Fig. 12 Visual information is composed of polarity and frame information. The idiotropic vector is defined as the contribution of the own longitudinal body axis.

A visual-vestibular spatial orientation model

Putting these assumptions together, we come up with a model as sketched in Fig 15. According to this model, spatial orientation is thus characterised by at least four variables, in this case four vectors, with three (Cartesian) components each. These variables are linear acceleration, linear velocity, angular velocity, and our sense of attitude means of the estimate of the gravitational vector. Because linear acceleration is closely linked to force by Newton's second law ($\mathbf{F} = m\mathbf{a}$), the perception of acceleration may also be closely related to force perception. The estimation of the gravitational vector is also called the subjective vertical (SV). Due to the different interactions involved, the four variables may all behave differently, and are therefore (partly) independent. When characterising spatial orientation this way (i.e. by means of four vectors), it will also be evident that spatial orientation is a complex matter, which interpretation is further complicated by our limited intuitive sense to form a notion of (mainly angular) motions and attitude in three-dimensional space.
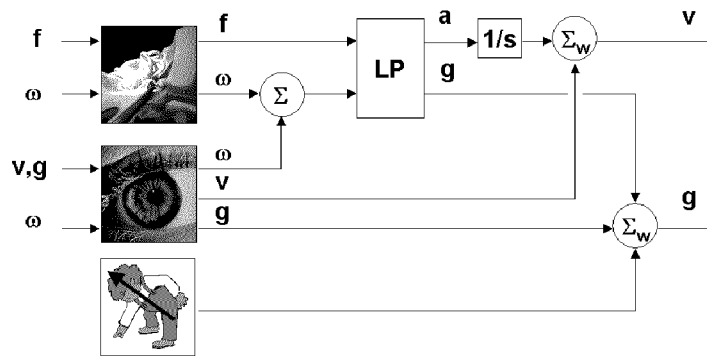

Fig. 15. Visual-vestibular interactions. The vestibular system takes into account the specific force and angular velocity (**f** and **ω**), while the visual system determines linear velocity, attitude, and angular velocity (**f, g** and **ω**). Vestibular and visual velocity signals are assumed to add linearly. The separation of the specific force into an inertial and a gravitational component conform Fig. 12 is represented by the LP-block. Visual velocity and time-integrated vestibular acceleration are also added linearly, however with a dominance of visual information. Vestibular and visual attitude signals are weighted linearly, and combined with the idiotropic vector.

To exemplify this complexity, and yet clarify the use of this model in a relatively simple way, we will consider motion and attitude perception during a takeoff. There are two different ways of simulating a takeoff. One is by means of a Stewart platform, the other uses a centrifuge. The latter is of especial relevance to military aviation.

Two examples

Stewart platform: When only mimicking moderate forward accelerations like that of a typical takeoff of a civil aircraft, a Stewart platform can be used. A takeoff experiment by Groen et al. (2001), using the Stewart platform of the National Aerospace Laboratory in Amsterdam, the Netherlands (See Figs. 16 and 17), is of special relevance here. Their motions are well defined, and they asked (six) experienced aviators for motion and attitude judgements that comply very well with the presently defined model outputs. We will here use a motion profile that was judged to be good, as well as one that was judged to be bad, both intended to mimic a stepwise varied linear acceleration to a level of 0.35g. In addition we will calculate what would have been the outcome given an idealised real takeoff, as well as one with a fixed base simulator. Note that in all cases with vision, the visual stimulus only moved horizontally conform the forward linear acceleration.
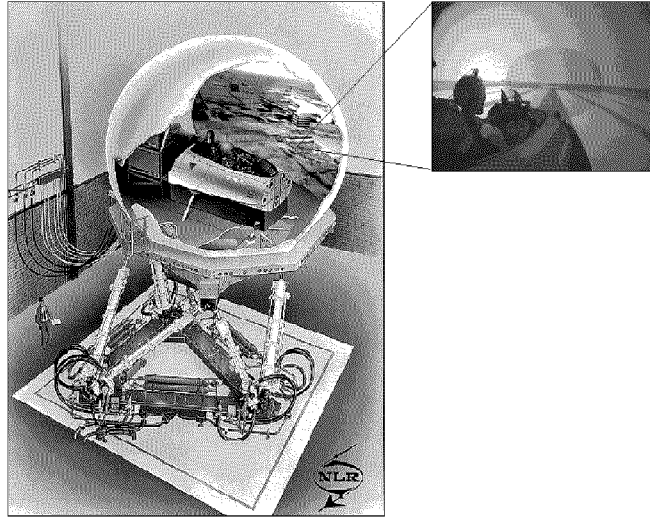
Fig. 16. The Dutch National Simulator Facility, a Stewart platform, as used by Groen et al. (2001) for their take-off experiments.
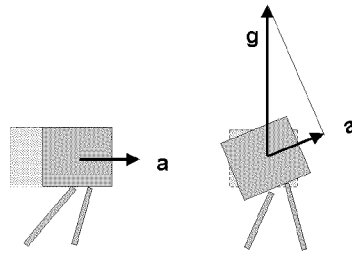

Fig. 17. A linear forward acceleration can be induced by surge as well as by tilt, using the projection of the gravitational acceleration onto the subject's x-axis. However, due to the limited stroke of a Stewart platform, linear acceleration by surge can only be of a short duration. A tilt, on the other hand, can only be realised slowly in order to remain unnoticed (i.e. by the SCC). The typical acceleration profile of a simulator run therefore shows a dip in the realised profile.

To show the effect of vision on the final results, we also performed all calculations as if no vision had been present. Because the effects of velocity and attitude along the x-axis are largest, we will restrict the data presentation to the projections of the predicted perceived velocity and attitude vectors on the x-axis. Attitude is recalculated in terms of the angle between the x- and z-component of the SV. These data are shown in Fig. 18.

Without going into detail (the interested reader is referred to Bos et al., 2001, 2002), these results can be read as follows. The closer the simulated responses are to the predicted response of a real takeoff the better the run may be anticipated to be. As far as the linear motion perception is concerned (acceleration and velocity), there seems to be not much difference between the predicted responses of the good run and that of the bad run. Here, the effect of vision is most evident, especially in the condition without vision, and this can be understood by the fact that in a real takeoff the vestibular system still experiences a true forward acceleration, while in the simulator only a physical tilt is present. Angular velocity is always below 3°/s, which is assumed to be below the threshold for angular motion perception. When looking at the attitude perceptions, then there is a significant difference between the good and the bad run (most clearly seen in the without vision conditions), the bad run typically showing a greater discrepancy with respect top the perception of a real takeoff. The perception of attitude may therefore be considered to be a (major) factor determining the subjective judgement on the fidelity of the simulator motions. With a fixed base simulator, of all variables that determine spatial orientation, only linear velocity is at stake, and this will generally be too delicate for a faithful sense of spatial orientation. Hence, it seems justified to conclude that indeed the quality of a simulator motion can objectively be rated by the difference between the predicted perception of the simulated motion with respect to that of a real motion. Moreover, a model like presented here gives the

opportunity to explain why a good run is good, and a bad run is worse, and it offers the possibility to optimise motion filters by an objective criterion as mentioned, instead of just an intuitive manipulation of motion filter parameters by an experienced technician.
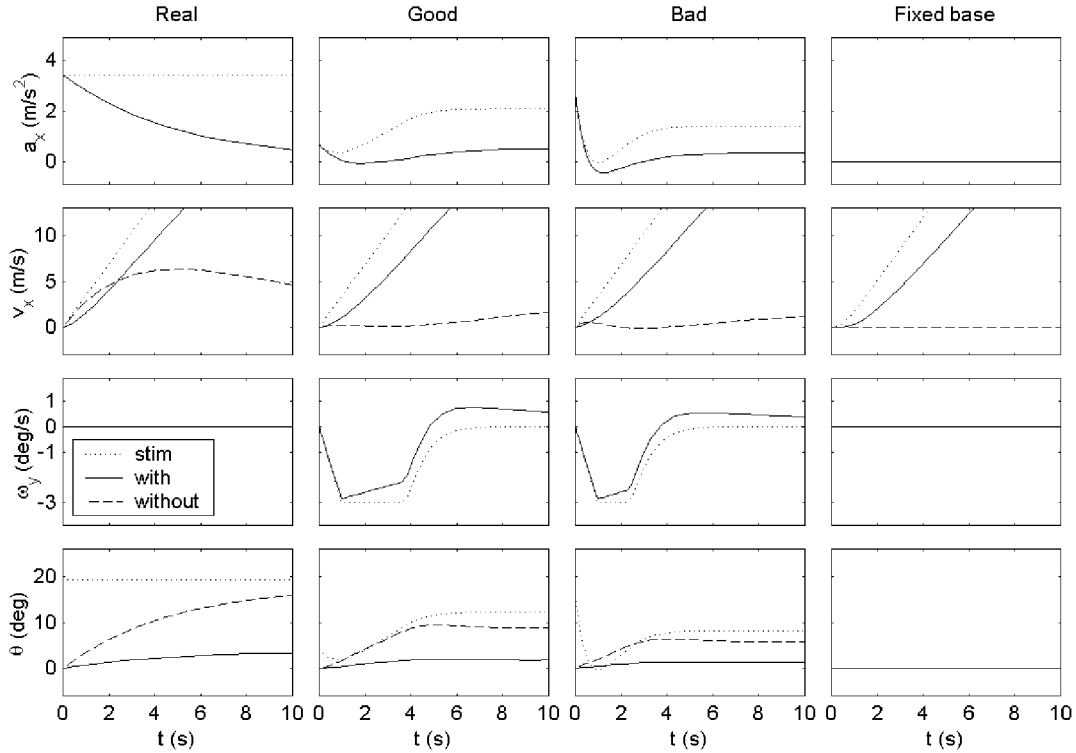
Fig. 18. Model predictions regarding a moderate takeoff simulated by means of a Stewart platform. Left: results of a hypothetical real takeoff. Second left: results of a simulator run judged to be good. Second right: results of a simulator run judged to be bad. Right: results of a simulation with a fixed base simulator, i.e. only visual flow is present. Shown are the predicted perceptions of acceleration (a_x and stimulus acceleration with dotted lines), linear velocity (v_x), angular velocity (ω_y; note that pitch is the only true rotation involved), and tilt (θ). Results with vision are shown by solid lines, without vision by dashed lines.

Centrifuge: A Stewart platform is insufficient when simulating a takeoff with a higher sustained acceleration (i.e. >1g), and this is especially relevant in military aviation. A number of controlled flights into the sea right after nightly catapult launches from aircraft carriers during WW-II and the Korean War can be ascribed to the fact that aviators compensated for the apparent pitch up induced by the high forward linear acceleration (Buley & Spelina, 1970). It is also assumed that every year today a number of controlled flights into terrain can be attributed to this phenomenon. Because long lasting high G-loads can be induced by a centrifuge, this type of stimulation has been used to simulate a catapult launch from an aircraft carrier (e.g. Cohen et al., 1973). When the somatogravic effect (see introduction) is elicited by a centrifuge, however, there is concomitant rotation, definitely supra-threshold, and this rotation does have a large impact on the somatogravic effect (Bos & Bles, 2001). The effect of concomitant angular motion induced by a centrifuge on motion perception is most clearly demonstrated by means of a long lasting linear acceleration as will be considered here. We programmed a hypothetical centrifuge arm length of 3m for these predictions, resulting in a centripetal acceleration of 3g (i.e. $\omega \approx 180°/s$). We here also assume a visual stimulus to be present that is only moving in a forward direction according this centripetal acceleration. The model parameters are kept equal to those for simulating the Stewart platform conditions. Fig. 19 then shows the results, analogous to those of Fig. 18. Because the only angular motion involved here is about the *z*-axis, this will also be the only angular velocity component shown here.
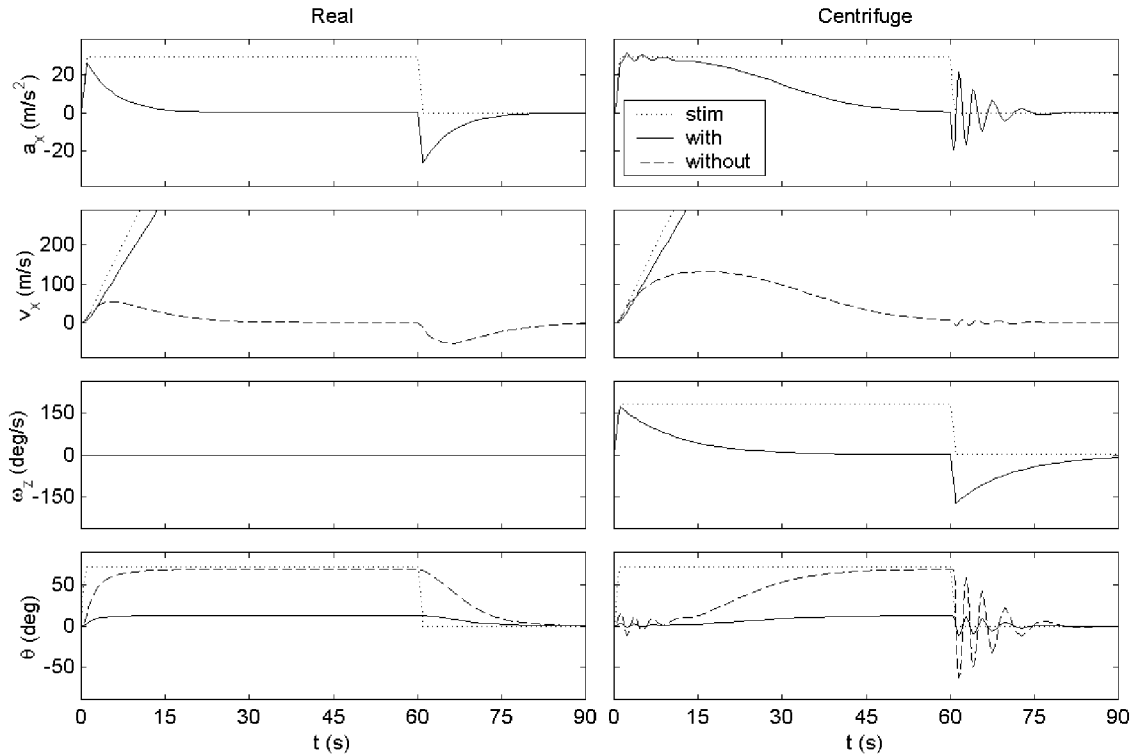
Fig. 19. Model predictions regarding a high-G takeoff. Left: results of a hypothetical real takeoff. Right: results of a centrifuge run. Shown are the predicted perceptions of acceleration (a_x and stimulus acceleration with dotted lines), linear velocity (v_x), angular velocity (ω_z; note that yaw is the only true rotation involved), and tilt (θ). Results with vision are shown by solid lines, without vision by dashed lines.

Most differences concerning motion perception are analogous to the results discussed concerning the Stewart platform takeoff. As opposed to the Stewart platform, however, the perception of linear velocity is larger in the centrifuge as compared to that in a real takeoff when vision is absent. This is due to the concomitant angular motion. Angular velocity is one of the main problems in simulating a high G-load takeoff anyhow. Here, the perceived angular velocity is over 180°/s, which is far above the perception threshold of 3°/s. The angular motion perception is therefore extremely disorienting, and this fact can not be set aside. The most interesting parameter of spatial orientation here concerns the perception of attitude, or the SV. Qualitatively, the model does predict the perception of tilt as it has been observed (see Fig. 6). Note that the curve shown in Fig. 6 represents an average, and the oscillations after centrifuge deceleration have probably been canceled resulting in a large asymmetry. The model also predicts this asymmetry. However, we know now that the perception of tilt is much different in the real situation as compared to a simulated condition. After some initial oscillations (which are no model simulation artifacts), the tilt increases much slower as compared to the tilt due to a linear acceleration without concomitant angular motion. We have previously shown the explicit dependency on angular motion (Bos & Bles, 2001). The most dramatic effect, however, and we have observed this in practice (Bos & Bles, 2001), appears at centrifugation offset. Due to the high-pass characteristics of the SCC, there is a strong rotation sensation after motion cessation, and this signal rotates the subjective vertical (as mathematically described by equation 2). The projection of the SV onto the x-axis therefore results in the oscillation as observed. Because acceleration perception is the opposite of tilt (see Fig. 7), acceleration perception will also oscillate in this case. Hence, also by this example, many peculiarities of spatial (dis)orientation can now be understood better, and predicted accordingly. For further details, the reader is again referred to the paper by Bos et al. (2002).

DISCUSSION

We here presented a model including visual-vestibular interactions describing the basic properties of the human spatial orientation system. It hence also explains and describes spatial *dis*orientation. Though not elaborated in detail here, and confined to visual and vestibular cues, the model seems successful in predicting motion and attitude perceptions. We did elaborate the model using a takeoff manoeuvre in real, when simulated by means of a Stewart platform, and by means of a centrifuge. We anticipate that the model, possibly after some further elaboration and optimisation, will also adequately explain and predict the perceptions due to other manoeuvres typical for military aviation, including those of super agile aircraft that have not yet been explored yet.

One extension of the model is likely that by an internal model. In the simple servo model of Fig. 1, sensory deficiencies and CNS delays will directly deteriorate the system's performance. To overcome these problems, it is nowadays believed that the central nervous system uses a so called internal model of the body dynamics, that, when fed with a copy of the motor commands (the efference copy), may give a prediction of body motion that is more accurate than that estimated by our sensory system (Bos & Bles, 2002). If this internal model next includes a copy of the sensory dynamics as well, the difference between true sensory and internal model afferents may be used in addition for adaptation purposes. Optimally this difference should, of course, be zero. We have previously shown that this difference, or conflict, when modelled properly, correlates well with motion sickness (Bos & Bles, 1998, 2002; Bles et al., 2000). Another extension concerns the addition of somatosensory cues, also referred to as "the seat of the pants". If, for example, acceleration perception is linked with force perception as stated earlier, than we will need the interaction with somatosensory cues to command the oscillating perception of acceleration after the centrifuge deceleration in Fig. 19.

Irrespective these possible and likely required extensions of the here presented model, it can be stated by the present knowledge as condensed in Figs. 12 and 15, and the elaboration thereof, that the indistinguishability between accelerations due to motion (i.e. inertial accelerations), and those due to gravity, is the basis of our inability to adequately estimate our sense of motion in all conditions. Hence, *the equivalence principle can be considered to be the main cause of spatial disorientation.* Normally, i.e. under self propelled motion, the solution our CNS applies to disentangle these accelerations does work well. It is, however, only under unnatural conditions, such as sustained hyper G-loads, that anomalies come forth. These problems are next further enhanced by an insufficiency of our angular rate sensors, the semicircular canals. Also for these sensors it holds that under natural conditions they function near perfection, and it again is only under unnatural conditions, such as a sustained constant angular velocity, that they fail.

When vision is present, the visual information normally dominates vestibular cues. However, as demonstrated by the takeoff experiment by Groen et al. (2001) and the succeeding model predictions of motion and attitude perception, visual dominance is not complete, and vestibular cues will always (at least in case of a functioning vestibular system) make their influence felt. Moreover, especially in military flight, the aviator may be deprived from external visual cues due to darkness, bad weather, or hooded conditions, or he may even falsely interpret visual cues (like in autokinesis, false horizon, and lean on the sun illusions). Vestibular cues are the primary factor in determining one's spatial orientation then. Most, if, by definition, not all, SD-mishaps just concern such poor conditions. We will have to reckon that both the visual and a vestibular systems have a limited range of (near) perfection, and the high performance flight environment is definitely out of that range.

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